FOAM COATING OF FILTRATION MEDIA

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Degree Programme in Paper, Textile and Chemical Engineering
Option of Chemical Engineering

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ABSTRACT

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The objective of this thesis was to find out if foam coating could be applied to non-woven filtration media. The goal was to increase collection efficiency without significantly decreasing air permeability.

In the theoretical part, foams and their characteristics were the centre of attention. Coating in general and, of course, foam coating were also studied. The empirical part consisted of series of foaming experiments and pilot scale coating experiments. In the foaming experiments different coating fibres and foaming agents were tested.

Despite a persisting fibre flocculation problem, there were some promising results. Unfortunately the project ran out of funds before any commercially applicable results were achieved.

The appendices of this thesis include confidential information.

Key words: foam coating, nonwoven, filtration media, air permeability, collection efficiency

CONTENTS

ABBREVIATIONS AND TERMS

Collection efficiency	the percentage of particles of a certain diameter that do not permeate a filter
Colloid	colloidal system; molecules or polymolecular particles with at least one dimension roughly between 1 nm and 1 μm dispersed in a medium
PES	polyester
PSF	particle stabilized foam
PVA	polyvinyl alcohol
SDS	sodium dodecyl sulphate
Soft matter	material with physical properties somewhere between solids and Newtonian fluids, for example colloids, gels, polymer melts and solutions, complex liquids
Surfactant	surface active agent; tenside

1 INTRODUCTION

This thesis was made for Ahlstrom Tampere. The goal of this thesis was to determine if foam coating could be applied on the products of Ahlstrom Tampere, and to identify the possible benefits. The ideal was to increase the collection efficiency of a filtration medium without substantially decreasing its air permeability. The theory behind foams and foam coating were also studied.

The Tampere plant of Ahlstrom Tampere is a part of Ahlstrom Corporation's Filtration business area. Other business areas of the corporation are Building and Energy, and Food and Medical. Ahlstrom is a manufacturer of high performance fibre-based products, wet laid nonwoven filtration media in the case of Tampere plant. (Ahlstrom Corporation 2015.)

The first part of this thesis covers the theory behind foam coating. In order to better understand the principles of foam coating, some basic characteristics of foams have to be discussed (chapter 2). After that, in chapter 3, some information on coating in general as well as foam coating is provided. After that comes the empirical part (chapters 4–7), followed by some discussion on the results in chapter 8.

The empirical part of the thesis was realized in cooperation with experts from VTT Technical Research Centre of Finland. The help and information received from senior scientists Tuomo Hjelt and Karita Kinnunen were absolutely invaluable. The empirical part consists of four sets of experiments including test runs, testing and reporting the test results.

2 FOAMS

According to a wide definition, foams are colloids in which gas bubbles are dispersed in a liquid, solid or gel. The bubbles are usually too large to be considered colloidal (radius $r > 1$ μm), but the thickness of the films between the bubbles is small enough. (IUPAC 2002.) A more precise definition suitable for this thesis is that foams are metastable dispersions of gas bubbles in liquids, stabilized by foaming agents (Colin 2012, 75).

2.1 Structure

Most commonly foams are mixtures of bubbles of different sizes. These bubbles are separated by films of liquid. At the meeting point of three neighbouring films, a channel is formed. These channels are called Plateau borders, named after renowned Belgian physicist and foam morphologist Joseph Plateau. At the junctions of these borders are small pockets of liquid, called vertices, as can be seen in figure 1. (Kinnunen, Hjelt & Kenttä 2012; Weaire, Tobin, Meagher & Hutzler 2012, 7.)

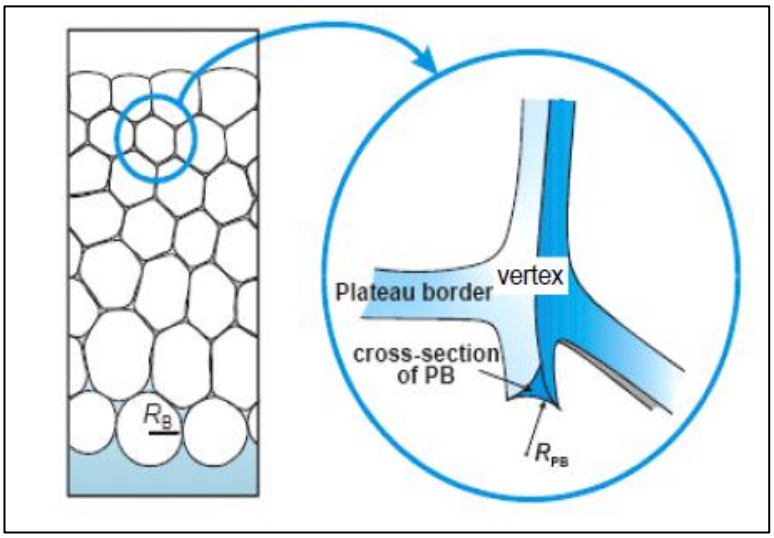


FIGURE 1. Foam structure (Kinnunen, Hjelt & Kenttä 2012)

The factor that impacts the morphology of a foam the most is its liquid content (see figure 2). At the dry limit the bubbles are packed close together and the liquid films can be considered infinitesimally thin. The bubbles form honeycomb like structures consisting of many types of polyhedra. The vertices are small enough to be considered

non-existent. At the wet limit the bubbles remain spherical with liquid separating them from each other. Real foams are something in between of these idealized models. Bubble size affects the liquid fraction; small bubbles tend to form wetter foams than larger ones. (Weaire et al. 2012, 7–11.)

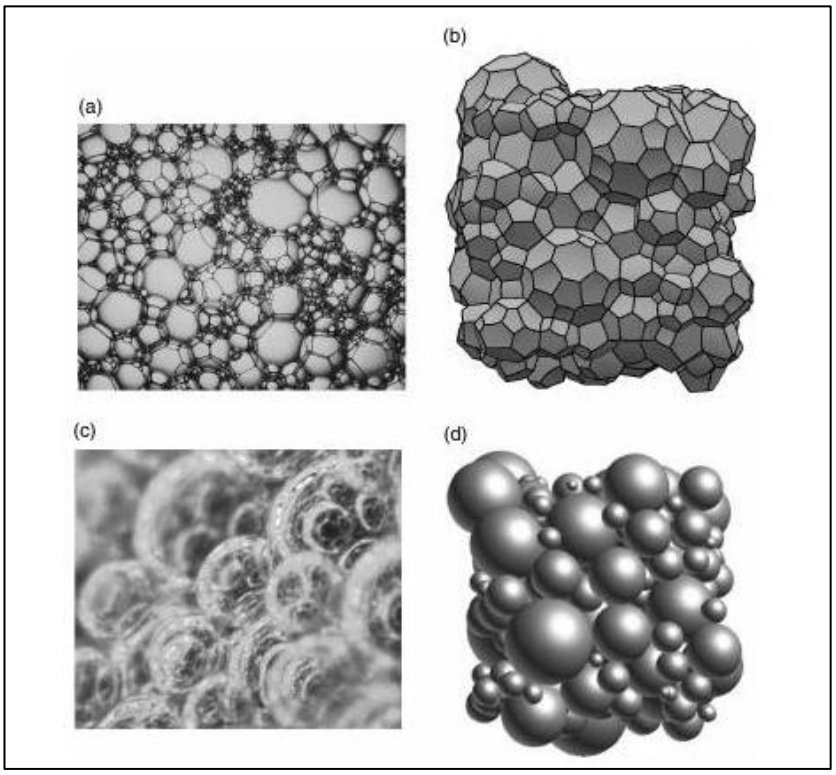


FIGURE 2. Photos (a and c) and models (b and d) of dry and wet foams (Weaire et al. 2012, 8)

2.2 Characteristics and Properties

One of the most prominent characteristics of a gas-liquid foam is its high specific surface area. The large area makes it highly suitable for interphase mass transfer processes. Also, a low interphase slip velocity allows a long contact time between gas and liquid phases. This also increases foams' mass transfer potential, which is the basis of foam coating. (Stevenson 2012, 1.)

2.2.1 Rheological Properties

Foams are an example of soft matter, and their mechanical behaviour is quite complex. When subjected to a small shear stress, foam acts like a soft solid (visco-elastic behaviour); elastically at low strains, plastically as the strain increases. If the shear stress exceeds yield stress, the foam starts acting like a shear-thinning liquid (visco-plastic flow). Shear-thinning means that the liquid's effective viscosity decreases as the shear rate increases. A charasteristic strain-stress curve of a foam is presented in figure 3. (Cox, 35; Denkov, Tcholakova, Höhler & Cohen-Addad 2012, 91.)

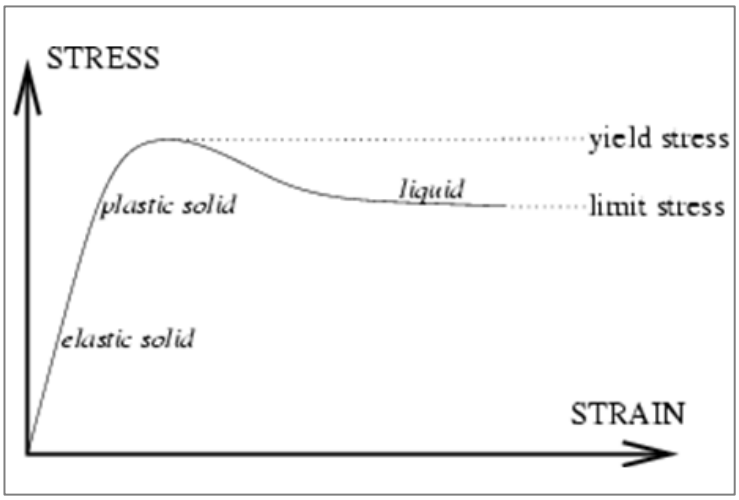


FIGURE 3. Characteristic strain-stress curve of a foam (Cox, 35)

When foams are in contact with solid walls, other rheological phenomena have to be taken into account. If the walls confining the foam are smooth, the foam slips on the wall. This can affect the results of rheological measurements as the shear rate cannot be deduced directly from the motion of walls. (Denkov et al. 2012, 91–92, 112.)

2.2.2 Ageing

The ageing of foams includes three interdependent processes: drainage, coarsening and coalescence. Drainage (or syneresis) means the redistribution of liquid, and coarsening (or ripening) is the process of gas redistribution between the bubbles. Coalescence is the rupturing of the liquid films between bubbles. (Colin 2012, 75; Koehler 2012, 28.)

Originally foam drainage only meant the fluid flow out of a foam. As the technological significance of foams has increased, scientific approach has caused the term to broaden its meaning to fluid flow between compressed bubbles. The driving force behind drainage is gravity. The process can be compared to liquid flow through a porous solid with a couple of considerable exceptions. First, foams are elastic and morph according to flow rate. Second, the pore equivalents of foams are liquid-gas interfaces, which are also flowing. (Koehler 2012, 27–29.)

The gas diffusion between bubbles causes small bubbles to shrink and large ones to grow. This drives the foam towards thermodynamic equilibrium as the average bubble size grows. The diffusion is driven by the differences of Laplace pressure in bubbles of different sizes (Colin 2012, 75). The increase in bubble size and induced internal dynamics greatly affect the foam's rheological and optical properties. (Pitois 2012, 59.)

2.3 Foam Generation

Foams are produced by introducing gas into a liquid. Different methods include blowing gas through a nozzle, sparging (blowing gas through a porous plug), blending, shaking, and nucleation of gas. The first two are mainly used for creating laboratory samples. (Weaire & Hutzler 2001, 47–48.)

The main difference between foams produced by different methods is the bubble size distribution. Blowing gas through a nozzle with a low, constant rate and gas nucleation produce a relatively monodisperse foam, i.e. a foam homogenous in bubble size. (Weaire & Hutzler 2001,48.)

2.4 Foam Stabilization

Foams consisting of bubbles in one-component liquids are unstable both thermodynamically and kinetically. This means foams have to be stabilized by separating the bubbles from each other. This can be achieved by adding surfactants or solid particles. (Kaptay & Babcsán 2012, 121.)

2.4.1 Surfactants

Surfactant is a term standing for surface active agent, also known as a tenside (Helmenstine). Surface active agents are amphiphilic which means that they have hydrophilic and hydrophobic parts. The hydrophobic head is non-polar, most commonly a hydrocarbon or fluorocarbon chain. The hydrophilic head can be anionic, cationic, non-ionic or amphoteric (both anionic and cationic; also known as zwitterionic). (Holmberg, Jönsson, Kronberg & Lindman 2002, 1–2, Som, Bhatia & Mohd. Yasir 2012.)

Surfactants gather at phase boundaries and decrease the amount of free energy at the surface. This stabilizes the phase boundary. For example, foams have a tendency to collapse into two separate bodies of liquid and gas in order to minimize surface area. The rate of separation can be significantly decreased by using a suitable surfactant. (Holmberg et al. 2002, 1–2.)

Sodium dodecyl (or lauryl) sulphate (SDS or NaDS, see figure 4) is an anionic surfactant. Its uses include cleaning detergents, toothpaste, shampoo, wetting agent and research in protein biochemistry. It also has potential as a microbicide (Piret, Désormeaux & Bergeron 2002, 17) and a chemical shark repellent (Sisneros & Nelson 2001, 127). (PubChem 2014.)

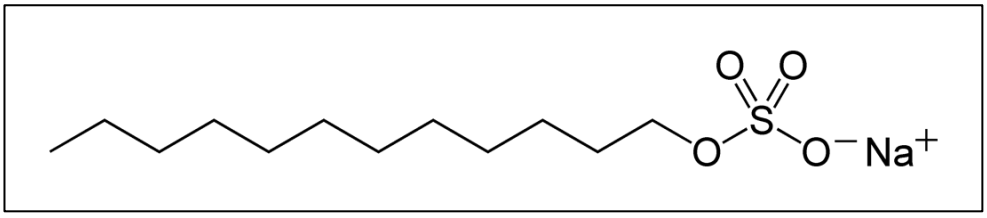


FIGURE 4. Chemical structure of SDS (Helmenstine)

Polyvinyl alcohol (PVA) is a polymer surfactant. From its structure (figure 5) can be seen that it has a 1.3-glycol structure. In other words it has a hydroxyl (OH^-) group on every second atom of its carbon chain. There are also some acetate groups, the amount of which depends on the degree of hydrolysis. (Hentschel 2009, 246.)

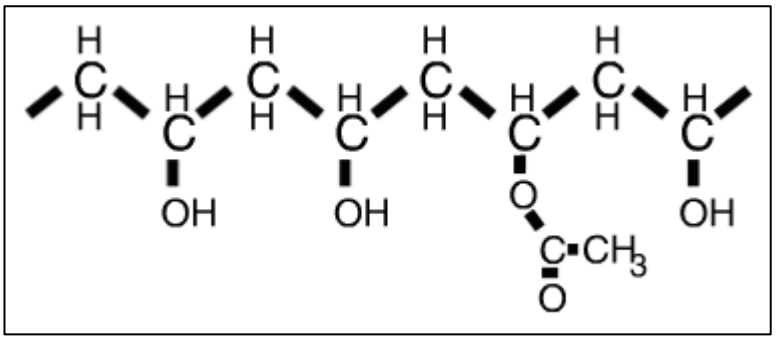


FIGURE 5. Chemical structure of PVA (Hentschel 2009, 246)

Unlike SDS, PVA is non-ionic which makes it more inert. This has a positive effect on the stability of the foam. On the other hand, foam made with PVA takes longer to form than its SDS equivalent. PVA also acts as a binder (Hentschel 2009, 250) which has its pros and cons. While PVA binds the coating material onto the web, it also decreases the air permeability of the media, and high air permeability is one of the most important properties of an efficient filter.

2.4.2 Particle Stabilized Foams

Foams can also be stabilized with solid particles, such as ceramic particles or protein-based nanoparticles. Foams formed this way are called particle stabilized foams (PSFs). In the foam all bubbles are covered by one or more layers of particles. This causes a capillary pressure which prevents the merging of the bubbles. (Kaptay & Babcsán 2012, 123, 138.)

PSFs are not in equilibrium thermodynamically. Their quasi-equilibrium state is, however, more stable than the suspensions' before foaming. This stability makes them superior when compared to foams stabilized by tensides. (Kaptay & Babcsán 2012, 138.)

3 FOAM COATING

Coating is a surface engineering process. Surface engineering is by definition "*changing the properties of the surface of a material to give performance which cannot be achieved by the surface layer or bulk alone*". The process includes depositing the coating onto the substrate surface, or forming the coating by reactions involving the substrate material. (Vuoristo 2012.)

In foam coating the foam acts as a carrier phase. The coating material is transferred in the vertices of the foam. This means that the foam has to be wet enough to have vertices of sufficient size. When the foam is applied on the web, its bubbles collapse due to absorption and the coating material descends on the surface of the textile. In fact, nano-scale materials adhere onto the web by surface forces with no need for a binder. (Kenttä, Kinnunen & Hjelt 2012; Kinnunen et al. 2012.)

Understanding behaviour of foams is very important when developing foam coating systems. For example, morphology of the foam changes with time and pressure. This has to be taken into account in order to ensure that the vertices of the foam remain large enough to carry the coating. On the other hand, if the foam is too stable and does not collapse, the coating will not adhere onto the surface properly.

Foam coating has numerous benefits compared to more traditional coating methods. One is related to occupational safety. There are no airborne particles as there might be in case of spray coating, for example. This is noteworthy as nanoparticles may be harmful when inhaled (SCENIHR 2006, 24).

4 FOAMING EXPERIMENTS I

4.1 Purpose

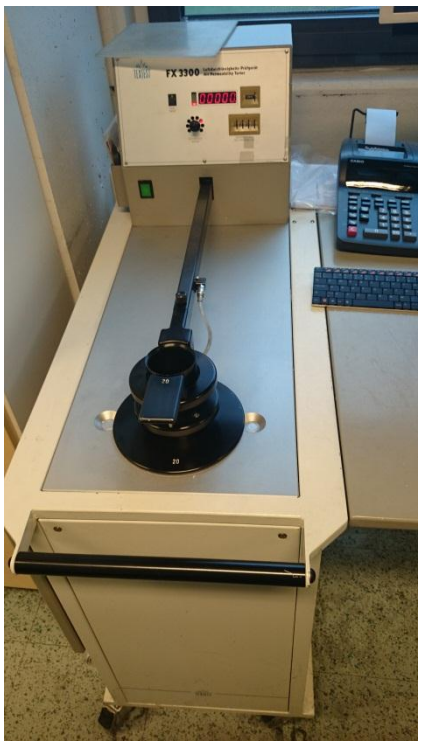
The main objective of this first set of experiments was to find out if the foams carrying the desired fibres could be made in the first place. This included testing with seven different fibres in two different consistencies. It was also tested how a binder already used in production on the plant affected the foam. In addition, some preliminary coating experiments on two different media were performed.

4.2 Execution

The first part of these experiments was pre-testing the sheets that were to be coated. 28 A4 sheets — from which collection efficiency had already been tested as a part of quality control — of medium A (synthetic air filter with micro glass fibres) were chosen. They were then weighed to determine their basis weight (according to equation (1)), and their air permeability was measured with Textest FX 3300 tester (picture 1). Another 28 sheets of medium B (synthetic air filter, considerably more permeable than medium A) were chosen and tested in the same manner as the A sheets. The results are shown in appendix 1.

$$\rho_A = \frac{m}{A} = \frac{m}{0.062456\ \mathrm{m}^2} \tag{1}$$

where ρ_A is the basis weight (in g/m^2), m is the mass of the sheet in grams and A is the area of the sheet (m^2).



PICTURE 1. Textest FX 3300 Air Permeability Tester

The second part was the actual foaming experiments. First, a fibre slush with the consistency of 2 % was prepared according to the fibre manufacturer's instructions. 50 ml of the slush was measured into a bowl and a few millilitres of surfactant were added. SDS was tried first but as it caused flocculation already in the bowl, PVA was used instead. The mixture was then foamed with a domestic hand mixer with beaters (OBH Nordica Chilli, see picture 2). A hand mixer was recommended (by VTT senior research scientist Tuomo Hjelt) over a laboratory mixer because it is designed for whipping foams whereas laboratory mixers are designed for mixing.

PICTURE 2. Hand mixer with beaters (OBH Nordica)

50 ml of fibre slush produced about 500 ml of foam. Two tablespoons were then scooped pile high of the foam and dosed on an edge of a dry sheet. The foam was then spread using a coating blade. The sheet was dried a little with a hair dryer and then left to dry until the next day. The procedure was then repeated with 10 ml of the slush diluted with 40 ml of water, with each of the fibres 1–7. All in all there were 14 foams and each was used to coat two sheets of medium A and two sheets of medium B.

Then the effect of an acrylic binder on foaming was tested. In order to do that, some of it was mixed in a bowl without any additives.

The next day the sheets were tested again. They were weighed and their air permeability was measured. Collection efficiency measurements (see instrument in picture 3) were started with the sheets that had been coated with the thicker slush to see if there was any difference. The sheets with the lower consistency coating were only to be tested if the other ones indicated any change to be expected. For the most of the sheets, air permeability was measured after collection efficiency because there was a concern that the coating material might be blown off during the air permeability measurement. The results are shown in appendix 1.

PICTURE 3. Collection efficiency tester

4.3 Conclusions

After finding a suitable surfactant for this method, all the foams could be made with ease. However, the crude application method caused the fibres to flocculate on the surface of the sheets. This can be seen from picture 4.

PICTURE 4. Sheet B2 (size A4)

There were no significant changes in the properties of the media (either A or B). It is impossible to calculate what the amount of fibres coated would be theoretically because of the inaccurate measures used and the flocculation phenomenon. However, it is safe to assume most of the coating ended up in the grains, which, while increasing the basis weight, have virtually no effect on the air permeability or collection efficiency.

In most of the cases with medium A, the collection efficiency had in fact decreased since the first measurements. This was most likely due to drying of the medium, as moisture content has a considerable impact on the filtration properties of wetlaid

nonwovens. The first measurements had been made shortly after production, not giving the product time to achieve normal moisture equilibrium, after all. This factor was taken into account in the following experiments by drying the samples before testing.

The acrylic binder was found not to hinder foaming at all. In fact, it could actually function as a foaming agent. Perhaps it could be used to bind the coating fibres in place.

5 PILOT RUNS

5.1 Purpose

Upscaling from laboratory to pilot scale was executed. The goal of these experiments was to find out if foams similar to those prepared in the foaming experiments could be applied on a web using equipment rented from VTT. Both dry sheets and wet newly formed web were tried out. Also, the effect of different parameters was studied.

5.2 Execution

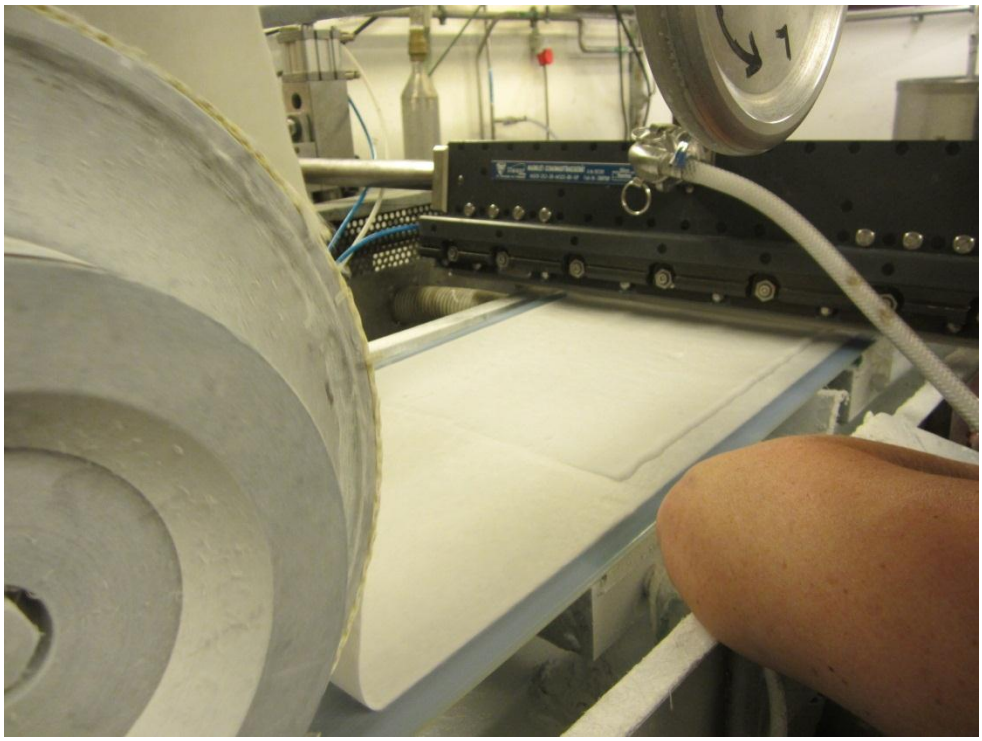
Before the actual pilot runs, some sheets of medium C were prepared. Medium C is a full synthetic air filter with micro glass (similar to medium A but with a smaller amount of glass fibre). They were first dried to improve the comparability of the results before and after coating. Their air permeability and collection efficiency were then tested as in the previous set of experiments.

The equipment consisted of the pilot machine of Ahlstrom Tampere plant and foam coating equipment from VTT. The pilot machine is a wetlaid textile machine with a three layer headbox. The foam coating equipment consisted of a foam generator and an application nozzle.

The foam suspension (water, fibres and surfactant; see appendix 2) was first mixed in an open tank by hand or with a mixer. The suspension was then pumped into the rotor-stator (on the right hand side of picture 5) of the foam generator. There it was mixed with air to produce the foam. When the foam was formed, it was conveyed to the nozzle through a long hose. The hose needs to be long enough to create a sufficient pressure to maintain the stability of the foam.

PICTURE 5. Rotor-stators of the foam generator (Kinnunen et al. 2012)

The coating can be seen in action in picture 6. In the picture the web is moving towards the camera. The foam is applied onto the web (or ready sheet) from the application nozzle (black). The foam collapses as it meets the vacuum box (underneath the bluish wire). The nozzle was installed in the location of the binding station so the web was not bound as it usually is. It was held together with partly melting bi-component fibres.



PICTURE 6. Foam coating in action

Finally the product was dried in the drier of the pilot machine. Before testing it was also dried in the oven as the previous samples.

5.3 Conclusions

The results for the reference and coated samples are presented in appendix 3, along with some of the run parameters. The collection efficiency of the dry sheets improved by some percentage points. However, there was no significant change in the properties of the newly laid web. This was of course considered a major setback as this setting was more similar to actual industrial applications.

There were some problems regarding the equipment used. Especially micro glass fibres grained during motorized mixing prior to foaming. It was concluded that the shear forced were too great. Also, some graining was caused by abrupt collapse of the foam. The suction of the vacuum box situated after the foam application was too strong. In addition, some fibres formed rope-like structures inside the rotor-stator, causing the fibre content of the foam to drop. It was discussed if the other model (on the left hand side of picture 5) would be better when using short artificial fibres. The rotor-stator selected for these experiments was better for viscous liquids (e.g. suspensions with water-absorbent natural fibres). The other option was not readily available, however.

6 FOAMING EXPERIMENTS II

These experiments were executed in the testing facility of VTT in Espoo. The goal was to study different factors in mixing and foaming a micro glass fibre slush and a polyester nano fibre slush, in order to minimize the graining phenomenon. A few sheets of medium D were also coated by hand. Medium D is similar to A and C but with no glass fibre.

6.1 Mixing Experiments

First, the effect of adding a surfactant (SDS) to a fibre slush was studied. When comparing 0.1 m-% glass fibre slushes with and without added SDS, it was found that SDS decreased the pH value. It was agreed that this change did not cause the flocculation as the dispersing of the fibres requires a low pH environment to begin with. The fibre slushes were then applied on a glass plate in order to compare the level of dispersion. It was found that without the added surfactant the glass fibres tended to form a raft of sorts. With SDS the fibres remained dispersed; in other words the surfactant acted as it was supposed to.

The same tests were then performed with the PES slush. In this case there was no notable change in the pH, or the dispersion of the fibres.

6.2 Foaming and Coating Experiments

Two different foaming methods were tested. The first one was a household mixer as in the first set of experiments. The second one was a laboratory mixer equipped with a slightly bent round blade (see figure 6 for cross-section). With this type of a blade the shearing forces are less aggressive, and presumably this could decrease the flocculation phenomenon. Also, different methods of manually applying the foam on the sheets were tried out.

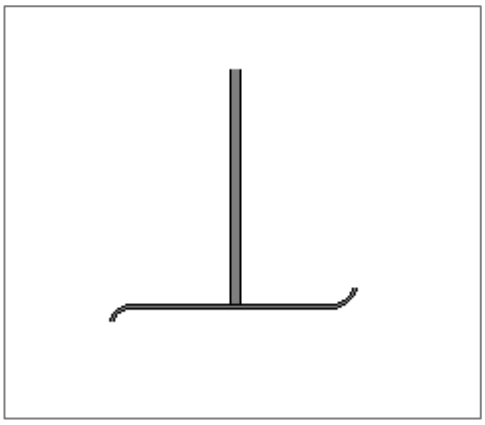


FIGURE 6. Cross-section of a gentler mixer blade

Both glass and PES fibre slushes were produced by the two methods. The foaming agent used was SDS in all but two cases. In these two cases non-ionic glucoside was used. It was tested to see if a non-ionic surfactant would work better with the fibres, even though glucoside seals the pore structure, making it unsuitable for filtration media. Another factor studied was how the moisture content of the sheets impacted the behaviour of the foam. This would affect the positioning of the coating apparatus in online applications. The compositions of the foams and methods used with each are presented in appendix 4.

All the sheets coated with foams made with the household mixer were discarded immediately after coating because the fibres flocculated excessively. The other sheets had their air permeability and collection efficiency tested back in Ahlstrom Tampere (see table 1). The flocculation still occurred but not as strongly. The samples were damaged somewhat during the transportation which may have caused some error.

TABLE 1: Foaming experiment II results

Sheet no	Air perm. $l/m^2/min$	Coll. eff. %	ΔP Pa
0 (ref)	1630	4,11	5
6	1390	7,41	6
7	1440	7,71	6
8	1560	7,22	6
9	1560	6,43	6
10	1270	10,35	7
11	1240	10,79	8
12	1210	7,52	8
13	1540	6,72	6
14	1560	7,29	6
15	1510	7,19	6
16	992	14,26	9

7 FOAMING EXPERIMENTS III

This set of experiments was conducted in order to clarify the behaviour of the foams in different mixing scenarios using current equipment by the pilot machine. The foam was prepared from a micro glass fibre slush with a consistency of 0.3 m-% with 0.25 g/L of SDS as a foaming agent. The mixture was foamed in the slusher for 15 minutes.

The first sheet was hand-coated with the foam described above. Then approximately 3 litres of the foam was taken to a separate vessel and mixed with a turbo mixer for 5…10 minutes. This foam was used on the second sheet. The remainder of the foam in the slusher was mixed for another 10…15 minutes, and then applied on the third sheet.

Once the sheets were dry, they were weighed to calculate their basis weight and their collection efficiencies were measured. The results are shown in table 2.

TABLE 2: Foaming experiment III results

Sheet no	Basis weight g/m^2	Coll. eff. %	ΔP Pa
1	84,91	84,06	45
2	88,06	51,49	26
3	79,51	39,55	21

The original basis weight of the sheets was approximately 70 g/m^2, and their collection efficiency 17 % with a pressure drop of 11 Pa. The coating process had significant effects on the properties of the medium. It was also seen that minimal mixing is the optimal method using this equipment. Sheet no 2 had gained the most glass fibres as seen from the weight gain. However, the glass fibres were apparently flocculated and did not improve the collection efficiency as much as in the case of the first sheet.

8 DISCUSSION

The goal of this thesis was to find out whether foam coating technology could be utilized at Ahlstrom Tampere. The most intriguing prospect was to find a coating that enhances the collection efficiency of filtration media. Significant increases were in fact achieved, but not without setbacks.

There was a fibre flocculation problem throughout the experiments. It remained unclear if it occurred because of the foaming, foam application, or some other factor. Most likely it was influenced by multiple factors, and clarification would require further testing.

Unfortunately the project ran out of funding before more experiments could be conducted. There were some promising results but nothing that could be commercially exploited at this point. The best results were gained by coating single sheets by hand, which is not easily upscalable, nor the results necessarily repeatable.

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APPENDICES

Appendix 1. Foaming experiment I results

(Confidential)

Appendix 2. Pilot run: Foams and run parameters

(Confidential)

Appendix 3. Pilot run: Result

(Confidential)

Appendix 4. Foaming Experiments II: Foams & Foaming and Application Methods

(Confidential)